Lepton-Number Violating Decays of Heavy Mesons

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The experimental observation of lepton-number violating processes would unambiguously indicate the Majorana nature of neutrinos. Various $\Delta L = 2$ processes for pseudoscalar meson M_1 decays to another pseudoscalar meson M_2 and two charged leptons ℓ_1, ℓ_2 ($M_1^+ \to \ell_1^+ \ell_2^+ M_2^-$) have been studied extensively. Extending the existing literature on the studies of these kinds of processes, we consider the rare decays of heavy mesons to a vector meson or a pseudoscalar meson. These processes have not been searched for experimentally, while they may have sizable decay rates. We calculate their branching fractions and propose to search for these decay modes in the current and forthcoming experiments, in particular at the LHCb.

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I. INTRODUCTION

The neutrino oscillation experiments have proved that neutrinos are massive [1–4]. However, the nature of neutrino masses is still one of the main puzzles in contemporary particle physics, *i.e.*, are neutrinos Dirac or Majorana particles? As we all known that the Majorana mass term violates lepton number by two units ($\Delta L = 2$). Thus, the unambiguous answer to the question above is the experimental observation of a lepton-number violating (LV) process.

Various $\Delta L = 2$ processes have been studied in the literature [5–9]. Among them Atre *et al.* [6] have studied 36 LV processes from K, D, D_s, and B decays, generically written by:

$$M_1^+ \to \ell_1^+ \ell_2^+ M_2^-, \tag{1}$$

where $M_i^\pm$ and ℓ_i^+ ($i = 1, 2$) denote charged pseudoscalar mesons and leptons, respectively.

Most of these processes have been searched for and the non-observation in the current experiments set the bounds on branching fractions. In turn, they led to some stringent constrains on the mixing parameters between Majorana neutrino and charged lepton directly. However, there are still more LV heavy meson decay modes that have not been studied experimentally, that may have sizable branching fractions in theory. In particular, heavy mesons (with c, b flavors) are easier to identify and the LHCb experiments will provide us with a large data sample. So as an extension of current existing calculations, we explore some new $\Delta L = 2$ decay modes in this paper. We mainly consider the rare decays of heavy mesons D, D_s, and B to vector meson final states. Since the LV heavy meson decay modes under our consideration have no experimental results, we cannot extract the mixing parameters through these decay channels like Atre *et al.* did.

However, those processes considered by Ali [5] and Atre [6] are clearly correlated with the decay modes under our consideration, with the same mixing parameters specified by the charged lepton flavors. We thus adopt the numerical values of mixing parameters extracted from Ref. [6], and the decay widths and branching fractions of heavy mesons for our processes can be predicted correspondingly. We choose the strongest constrains on mixing parameters from Ref. [6] as input in our study, in order to be conservative.

we mainly consider the heavy pseudoscalar meson D, D_s, and B to vector meson final states. From theoretical point of view, the decays of vector mesons may have different and uncorrelated rates from that of the pseudoscalars if there is other type of new physics, like a heavy particle exchange of either a pseudoscalar/scalar or a vector boson. Thus, it is well motivated to carry out the complementary searches for all of the availabel final states.

The paper is organized as follows. In Sec. II we outline the useful formulas to set the general notation. We list the constraints on mixing parameters and give the Monte Carlo sampling of the branching fractions as a function of the heavy neutrino mass in Sec. III, and draw our conclusion in Sec. IV.

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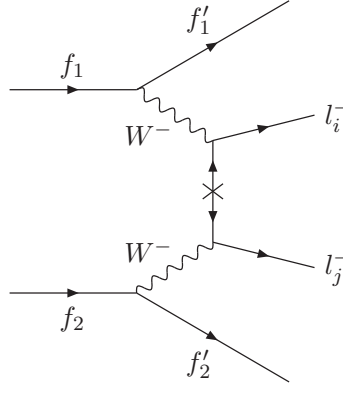[†]Electronic address: gl˙wang@hit.edu.cn

FIG. 1: Feynman diagram corresponding to the $\Delta L = 2$ processes via Majorana neutrino exchange.

II. THE GENERAL FORMALISM FOR LEPTON-NUMBER VIOLATING DECAY

The simplest renormalizable extension of the standard model (SM) to generate neutrino Majorana masses is to introduce n right-handed SM singlet neutrinos N_{bR} ($b = 1, 2, \cdots, n$). Therefore, the complete neutrino mass sector is composed of both Dirac masses that produced via the Yukawa couplings to the Higgs doublet in the SM, and possible heavy Majorana mass term $\frac{1}{2} \sum_{b,b'=1}^{n} \overline{N_{bL}^c} B_{bb'} N_{b'R} + h.c.$.

In terms of the mass eigenstates, the gauge interaction lagrangian of the charged currents now has the following form:

$$\mathcal{L} = -\frac{g}{\sqrt{2}} W_\mu^+ \left(\sum_{\ell=e}^{\tau} \sum_{m=1}^{3} U_{\ell m}^* \overline{\nu_m} \gamma^\mu P_L \ell + \sum_{\ell=e}^{\tau} \sum_{m'=4}^{3+n} V_{\ell m'}^* \overline{N_{m'}^c} \gamma^\mu P_L \ell \right) + h.c. \tag{2}$$

where $P_L = \frac{1}{2}(1 - \gamma_5)$, $\nu_m (m = 1, 2, 3)$ and $N_{m'} (m' = 4, \cdots, 3 + n)$ are the mass eigenstates, $U_{\ell m}$ is the mixing matrix between the light flavor and light neutrinos, and $V_{\ell m'}$ is the mixing matrix between the light flavor and heavy neutrinos.

The basic process with $\Delta L = 2$ shown in Fig. 1 with exchange of two virtual SM W bosons can be generically expressed by:

$$W^- W^- \to \ell_1^- \ell_2^-, \tag{3}$$

where $\ell_{l,2} = e, \mu, \tau$. The process can occur only if neutrinos are Majorana particles. Unfortunately, the transition rate of this $\Delta L = 2$ process encounters a severe suppression either due to the small neutrino mass like $m_{\nu m}^2 / M_W^2$, or due to the small mixing $\left| V_{\ell_1 m'} V_{\ell_2 m'} \right|^2$. However, when the heavy neutrino mass is kinematically accessible, the process may undergo a resonant production of the heavy neutrino, thus substantially enhancing the transition rate. The resonant contributions of heavy Majorana neutrinos to $\Delta L = 2$ processes involving two charged leptons and another pseudoscalar meson have been considered in the Ref. [6]. In this paper, we extend the study of the heavy Majorana neutrinos to $\Delta L = 2$ processes involving two charged leptons and a vector meson final state.

The Feynman diagram for the LV decay of heavy meson M_1 into two charged leptons ℓ_1, ℓ_2 and another meson M_2:

$$M_1^+(q_1) \to \ell_1^+(p_1) \, \ell_2^+(p_2) \, M_2^-(q_2). \tag{4}$$

is shown in Fig. 2. According to narrow-width approximation, the tree level decay amplitude when M_2 is a pseudoscalar meson is given as [6]:

$$i\mathcal{M}^P = 2 G_F^2 V_{M_1}^{CKM} V_{M_2}^{CKM} f_{M_1} f_{M_2} V_{\ell_1 4} V_{\ell_2 4} m_4 \left[\frac{\bar{u}_{\ell_1} \slashed{q}_1 \slashed{q}_2 P_R v_{\ell_2}}{(q_1 - p_1)^2 - m_4^2 + i\Gamma_{N_4} m_4} \right] + (p_1 \leftrightarrow p_2), \tag{5}$$

when M_2 is a vector meson, the tree level decay amplitude can be written as [6]:

$$i\mathcal{M}^V = 2 G_F^2 V_{M_1}^{CKM} V_{M_2}^{CKM} f_{M_1} f_{M_2} V_{\ell_1 4} V_{\ell_2 4} m_4 m_{M_2} \left[\frac{\bar{u}_{\ell_1} \slashed{q}_1 \slashed{\epsilon}^\lambda(q_2) P_R v_{\ell_2}}{(q_1 - p_1)^2 - m_4^2 + i\Gamma_{N_4} m_4} \right] + (p_1 \leftrightarrow p_2), \tag{6}$$

where G_F is Fermi constant; $V_{M_i}^{CKM}$ is the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements; f_{M_i} is the decay constant for meson M_i; q_1, q_2, p_1, p_2 are the momenta of mesons M_1, M_2 and leptons ℓ_1, ℓ_2, respectively. Here we consider the case when
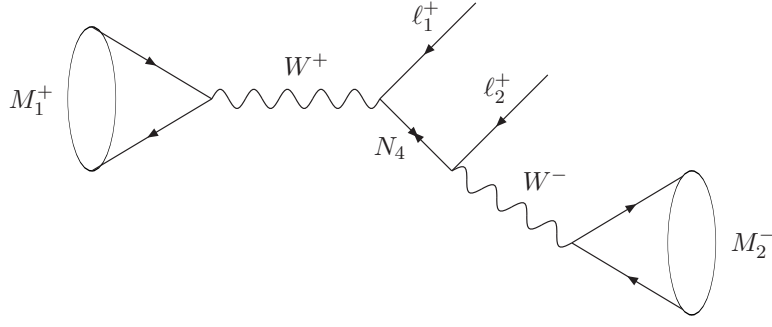
FIG. 2: Feynman diagram corresponding to the lepton-number violating decays $M_1^+(q_1) \to \ell_1^+(p_1)\ell_2^+(p_2)M_2^-(q_2)$.

TABLE I: The decay modes of the leptonic-number violating decays $M_1^+(q_1) \to \ell_1^+(p_1)\ell_2^+(p_2)M_2^-(q_2)$ and the ranges of the mixing parameters $|V_{\ell_1 4}V_{\ell_2 4}|$. The rages are calculated base on the correlative decay modes from the Ref. [6].

Decay mode	Mixing element $|V_{\ell_1 4}V_{\ell_2 4}|$	Range of m_4(MeV)	Range of $|V_{\ell_1 4}V_{\ell_2 4}|$
$D^+ \to e^+e^+\rho^-$		776 - 1869	0.002 - 0.998
$D^+ \to e^+e^+K^{*-}$		892 - 1869	0.002 - 0.998
$D_s^+ \to e^+e^+\rho^-$		776 - 1968	0.023 - 0.992
$D_s^+ \to e^+e^+K^{*-}$		892 - 1968	0.022 - 0.992
$B^+ \to e^+e^+D^-$	$|V_{e4}|^2$	1870 - 5278	0.236 - 0.992
$B^+ \to e^+e^+D_s^-$		1969 - 5278	0.231 - 0.992
$B^+ \to e^+e^+D^{*-}$		2011 - 5278	0.231 - 0.992
$B^+ \to e^+e^+D_s^{*-}$		2113 - 5278	0.232 - 0.992
$D_s^+ \to \mu^+\mu^+\rho^-$		882 - 1863	0.002 - 0.993
$B^+ \to \mu^+\mu^+D^-$		1975 - 5173	0.28 - 0.971
$B^+ \to \mu^+\mu^+D_s^-$	$|V_{\mu4}|^2$	2074 - 5173	0.28 - 0.971
$B^+ \to \mu^+\mu^+D^{*-}$		2116 - 5173	0.28 - 0.971
$B^+ \to \mu^+\mu^+D_s^{*-}$		2218 - 5173	0.327 - 0.971
$D^+ \to e^+\mu^+\rho^-$		776 - 1869	0.02 - 0.497
$D^+ \to e^+\mu^+K^{*-}$		892 - 1869	0.023 - 0.497
$D_s^+ \to e^+\mu^+\rho^-$		776 - 1868	0.02 - 0.497
$D_s^+ \to e^+\mu^+K^{*-}$		892 - 1968	0.023 - 0.497
$B^+ \to e^+\mu^+D^-$	$|V_{e4}V_{\mu4}|$	1870 - 5278	0.242 - 0.49
$B^+ \to e^+\mu^+D_s^-$		1969 - 5278	0.236 - 0.49
$B^+ \to e^+\mu^+D^{*-}$		2011 - 5278	0.236 - 0.49
$B^+ \to e^+\mu^+D_s^{*-}$		2113 - 5278	0.236 - 0.49

only one heavy Majorana neutrino is kinematically accessible and denote it by N_4, with the corresponding mass m_4 and mixing with charged lepton flavors $V_{\ell 4}$. Γ_{N_4} is the total decay width of the heavy Majorana neutrino, summing over all accessible final states. Then the partial decay width $\Gamma_{\ell\ell'}^{M_1}$ and the normalized branching fraction $BR = \Gamma_{\ell\ell'}^{M_1}/\Gamma_{M_1}$ for the LV process Eq. (4) can be calculated by the decay amplitude. Following the approach of Ref. [6], we will take the mixing parameter $V_{\ell 4}$ and the mass m_4 as phenomenological parameters.

III. MONTE CARLO SAMPLING FOR LEPTON-NUMBER VIOLATING DECAYS

The key step to calculate decay widths and branching fractions of the LV heavy meson decays is to determine the limits on the mixing parameters $|V_{\ell_1 4}V_{\ell_2 4}|$ and neutrino mass m_4 in Eq. (5) and Eq. (6). Generally speaking, one can determine limits on the mixing parameters from the LV heavy meson decay modes which have the current experimental limits on branching fractions and determine the mass of neutrino by kinematics. However, as mentioned in the introduction, since the LV decay modes which we studied with vector meson and several pseudoscalar meson final states are missing in directly experimental searches, so we cannot yet get information of mixing parameters $|V_{\ell_1 4}V_{\ell_2 4}|$ from those decays. We thus propose the direct searches for those modes in the existing and forth coming experiments such as in CLEO, B-Factories, and the LHCb. On the other hand, there are direct experimental results on the processes that may share common mixing parameters with those under our consideration. These decay modes given by Ref. [10] and Ref. [11] have been summarized and translated into the direct bounds in Ref. [6].
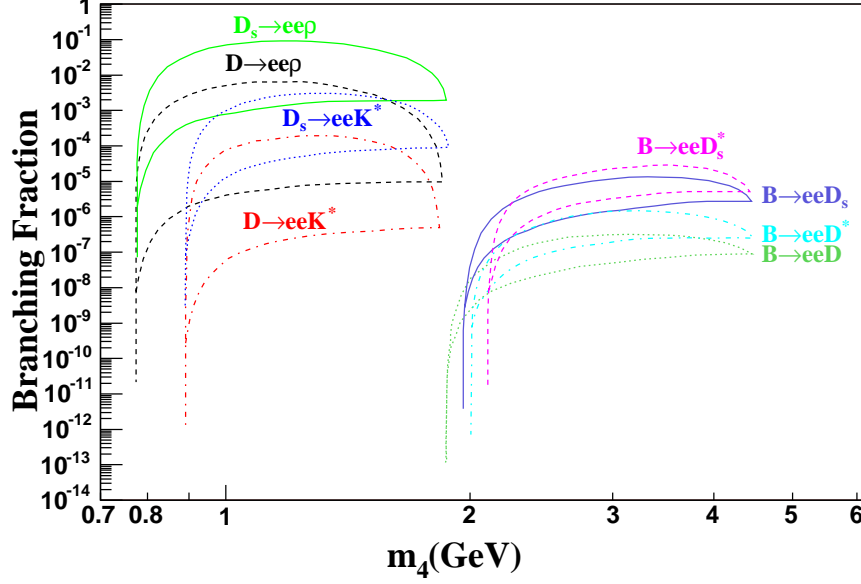
FIG. 3: Theoretically excluded regions inside the curve for the branching fraction of $M_1^+ \to e^+ e^+ M_2^-$ modes versus Majorana neutrino mass m_4. Regions below the curve are theoretically allowed. The curves of $D_s \to ee\rho$, $D \to ee\rho$, $D_s \to eeK^*$ and $D \to eeK^*$, denoted by solid line, break line, dotted line and dash-dotted line, respectively.

We thus adopt them for consistency and carry out our analyses. We first obtain the consistent limits on mixing parameters from some decay modes which have the current experimental bounds on the branching fractions for the heavy mesons with Ref. [6]. We then translated the limits on mixing parameters to the relevant decays modes of the heavy mesons D, D_s and B in the Table I. Depending on the flavors of the final state leptons, the mixing parameters probed are $|V_{e4}|^2$, $|V_{\mu 4}|^2$ and $|V_{e4}V_{\mu 4}|$, corresponding to the decay modes:

$$M_1^+ \to e^+ e^+ M_2^-, \quad M_1^+ \to e^+ \mu^+ M_2^- \quad \text{and} \quad M_1^+ \to \mu^+ \mu^+ M_2^-, \tag{7}$$

respectively. We list the most stringent limits on $|V_{e4}|^2$, $|V_{\mu 4}|^2$ and $|V_{e4}V_{\mu 4}|$ for the 21 new decay modes in Table I. The ranges of heavy neutrino mass m_4 in the Table I are determined by the kinematics accessible.

When performing the calculations, the input parameters for the CKM matrix elements and the decay constants of pseudoscalar and vector mesons are chosen as follows [10, 12–15]:

$$|V_{ub}| = 0.00359, \ |V_{cd}| = 0.2256, \ |V_{cs}| = 0.97334,$$
$$f_{D^\pm} = 0.2226 \text{ GeV}, \ f_{D_s^\pm} = 0.266 \text{ GeV}, \ f_{B^\pm} = 0.190 \text{ GeV},$$
$$f_{\rho^\pm} = 0.220 \text{ GeV}, \ f_{K^{*\pm}} = 0.217 \text{ GeV}, \ f_{D^*} = 0.31 \text{ GeV}, \ f_{D_s^{*\pm}} = 0.315 \text{ GeV}. \tag{8}$$

We note that there may be some errors in determining the decay constants [16], but they would not result in any qualitative difference for our predictions for the SM-forbbiten modes.

With these parameters and the limits on mixing parameters and corresponding mass ranges in the Table I, the decay widths and branching fractions of the heavy mesons D, D_s and B are calculated correspondingly. We perform a Monte Carlo sampling of the branching fractions and the mass of the heavy neutrino, $i.e.$, we plot the excluded region of the branching fractions as a function of m_4, as shown in Fig. 3 $\sim$ Fig. 5 for the modes in Eq. (7). The regions inside the curve are excluded by the direct experimental searches for the various LV decay modes of heavy mesons as obtained in Ref. [6]. The theoretical allowed regions are below the curve, $i.e.$, the regions below the curve are the currently allowed branching fractions for those LV heavy meson decay modes in the Table I.

From the figures, one can see that, if the heavy neutrino mass is located in the range from 1 GeV to 2 GeV, even with the most stringent constraints on mixing parameters, our theoretical predictions of upper bound of the branching fractions can be large, for example, $Br(D_s \to ee\rho) = 1.8 \times 10^{-3}$, $Br(D_s \to e\mu\rho) = 2.0 \times 10^{-3}$ and $Br(D \to e\mu\rho) = 1.3 \times 10^{-4}$, since about 2.4×10^6 D^+D^- [17] events and 5.5×10^5 $D_s^{*\pm}D_s^{\mp}$ [18] events have been collected by CLEO collaboration, these mentioned decay modes can be analyzed in the current experiment, which will provide us a strong information of 1 GeV to 2 GeV neutrino mass. But if the heavy neutrino mass is heavier, around 2 GeV to 4 GeV, we cannot use the D or D_s decay modes to detect the LV
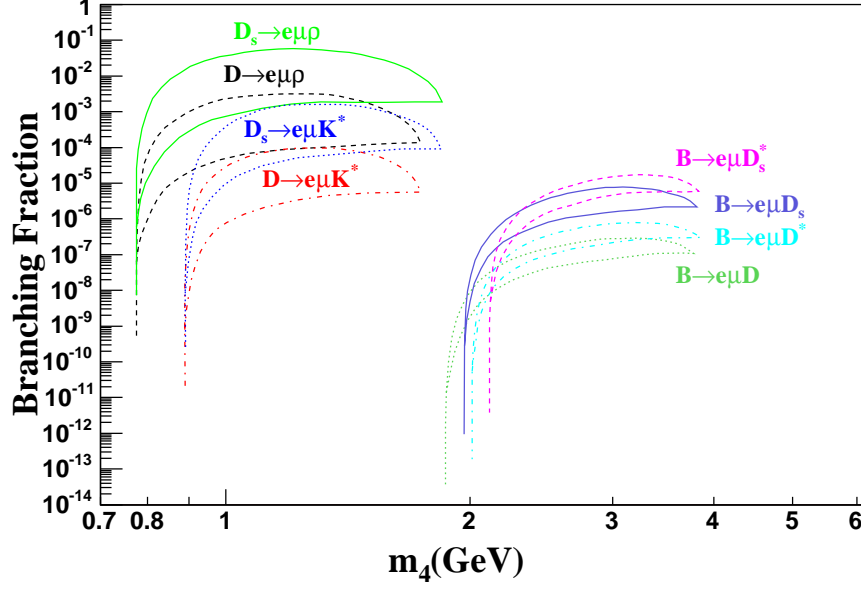
FIG. 4: Theoretically excluded regions inside the curve for the branching fraction of $M_1^+ \to e^+\mu^+ M_2^-$ modes versus Majorana neutrino mass m_4. Regions below the curve are theoretically allowed. The curves of $D_s \to e\mu\rho$, $D \to e\mu\rho$, $D_s \to e\mu K^*$ and $D \to e\mu K^*$, denoted by solid line, break line, dotted line and dash-dotted line, respectively.
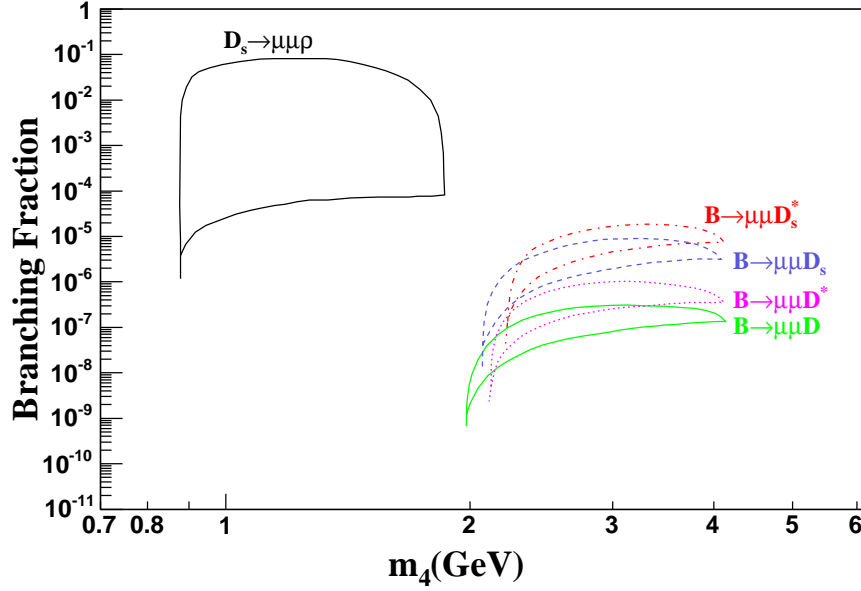

FIG. 5: Theoretically excluded regions inside the curve for the branching fraction of $M_1^+ \to \mu^+\mu^+ M_2^-$ modes versus Majorana neutrino mass m_4. Regions below the curve are theoretically allowed.

processes because of the kinetic limited, and the B decay modes are favored, whereas our predicted branching fractions of the LV B decay channels are lower than 8.0×10^{-6}, which cannot be detected by current B-factories, but in the forthcoming LHC experiments, around $10^{11} \sim 10^{12}$ B meson events are expected [19], all the LV B decays modes we studied can be effectively searched for by LHCb.

As a final remark, we would like to reiterate the advantage of our treatment in searching for the resonant production and decay of a Majorana neutrino in vector meson decay. Although kinematically limited, the signal rate for the rare meson decay is

substantially enhanced due to the resonant nature. In contrast to the similar decay channels as discussed in Ref. [5], where the intermediate Majorana neutrinos are far off mass-shell, the signal would be much weaker. Other contributions such as the box diagrams etc in Ref. [5] are all of similar nature and much smaller than those considered here.

IV. CONCLUSIONS

We extended the existing literature to consider the $\Delta L = 2$ rare decays of heavy mesons D, D_s, and B to a vector or pseudoscalar meson final state. Since there have not been any direct experimental searches on these LV heavy meson decay modes, we calculated their decay branching fractions and proposed to search for them in the existing and forth coming experiments.

We first re-evaluated the limits on the mixing parameters $|V_{e4}|^2$, $|V_{\mu4}|^2$ and $|V_{e4}V_{\mu4}|$ from some decay modes which have experimental limits on the branching fractions for the heavy mesons, and obtained full agreement with those in Ref. [6]. We then translated the limits on mixing parameters and corresponding mass ranges to the relevant decays modes of D, D_s, and B of our current interests as summarized in Table I. Finally, we calculated the decay widths and branching fractions for various LV decay modes by the limits on the mixing parameters and the heavy neutrino mass. We sampled the constraints on branching fractions as a function of the heavy neutrino mass as shown in the figures.

Although the prevailing theoretical prejudice prefers Majorana neutrinos, the unambiguous signature to prove the Majorana nature of neutrinos is the experimental detection of a LV process. A detection in one of the LV heavy meson decay modes studied in our analysis would imply LV and hence the existence of a Majorana neutrino. At present, about 2.4×10^6 D^+D^- [17] events and 5.5×10^5 $D_s^{*\pm}D_s^{\mp}$ [18] events have been collected by CLEO collaboration. So these decay modes $D_s \to ee\rho$, $D_s \to e\mu\rho$ and $D \to e\mu\rho$ *et al.* which we studied in the Table I might show up in the current experiments if the mass of the heavy neutrino is in the range 1 GeV $\lesssim m_4 \lesssim$ 2 GeV. But those B decay modes for the range of the heavy neutrino is 2 GeV $\lesssim m_4 \lesssim$ 4 GeV cannot be detected presently due to small branching fraction. Fortunately, in the forthcoming LHC experiments, around $10^{11} \sim 10^{12}$ B meson events are expected [19], which will provide us with chances of discovering all the LV B decays modes we studied. Therefore, we may have the opportunity to discover the LV process of heavy mesons B, D and D_s via the distinctive channels of like-sign dilepton production with no missing energy. Hadron colliders may serve as the discovery machine for the mysterious Majorana neutrinos.

ACKNOWLEDGMENTS

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